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Opinion Article

Innovative Multilayered Structures for a New Generation of Aircraft and Spacecraft

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The main improvements in future aircraft and spacecraft may depend on an increasing use of conventional and unconventional multilayered structures. Some of these configurations have already been in use for over three decades and include: layers made of isotropic alloys such as aluminum and titanium alloys which are widely employed and stacked with other materials in multilayered structures; carbon fiber reinforced laminates where the fiber orientation in each lamina and stacking sequence of the layers can be chosen to achieve the desired strength and stiffness for a specific application; sandwich structures with honeycomb or metallic foams used as core-layers which are lightweight with high bending stiffness; layered ceramic-metallic structures employed as thermal protection systems used, for example, in reentry space capsules. In the near future a variety of new unconventional materials could be used: for example, piezoelectric or piezomagnetic materials, which are commonly used in so-called smart structures as sensor or actuators depending on whether they use the direct piezoelectric/piezomagnetic effect or the converse piezoelectric/piezomagnetic effect; functionally graded materials, which have a continuous variation of physical properties in a particular direction in order to combine the desirable properties of the constituent phases to obtain a superior performance, avoiding the problem of interfacial stresses typical of classical multilayered configurations; and nanocomposites, which are multiphase materials, where at least one constituent phase has one dimension less than 100 nm, with unique physical, chemical, thermal and electromechanical properties which allow extensive potential applications. Layers made of such materials can be combined in different ways to obtain structures which are able to fulfill several structural requirements [1,2].

The next generation of aircraft and spacecraft (Figure 1) will be manufactured as multilayered structures under the action of a combination of two or more physical fields. Aerospace vehicles, and in particular their wings, are often exposed to high sun irradiation and thermal cycling. The related structures are simultaneously loaded by high thermal and mechanical loads and this is a typical example of a thermo-mechanical problem. A self-controlling and self-monitoring smart system is created when a network of piezoelectric/piezomagnetic actuators and sensors is embedded in multilayered structures. This new engineered class of materials has resulted in significant improvements in the performance of integrated systems, actuation technologies, shape control, vibration and acoustic control and condition monitoring [3,4]. Smart structures involve distributed actuators and sensors, and one or more microprocessors which analyze the responses from the sensors and use an integrated control theory to command the actuators to apply localized strains/displacements to alter the system response (Figure 2). A smart structure has the capacity to respond to a changing external environment (such as loads or shape change) as well as to a changing internal environment (such as damage or failure). Piezoelectric materials are the most popular smart materials, they undergo deformation (strain) when an electric field is applied across them, and conversely produce voltage when a strain is applied, and thus can be used both as actuators and sensors. Piezomagnetic materials are an alternative to piezoelectric materials, they produce deformations when a magnetic field is applied and have a magnetic potential when strain is applied. Smart structures are subjected to severe mechanical, electric and magnetic loads and usually operate in severe environmental conditions such as high temperature and high humidity, with negative effects on their performance. Unconventional materials, like piezoelectric and piezomagnetic ones, also introduce a response in terms of electric or magnetic potential when the structures are subjected to mechanical, hygroscopic or thermal loads. The problems related to smart structures which embed piezoelectric materials are defined as electro-mechanical problems. Thermal stress analysis of smart structures represents another interesting problem; one application is the use of piezoelectric layers embedded in multilayered structures in order to control thermal deformations, in this case a three-field problem is investigated (thermo-electro-mechanical coupling). In smart structures, when piezomagnetic materials are employed, coupled thermo-magneto-mechanical analysis is used. All these examples lead

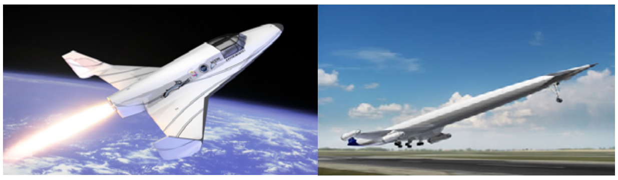

Figure 1: Examples of a new generation of spacecraft and aircraft. Project created by the XCOR Aerospace (on the left) and a European design project called LAPCAT A2 (on the right).

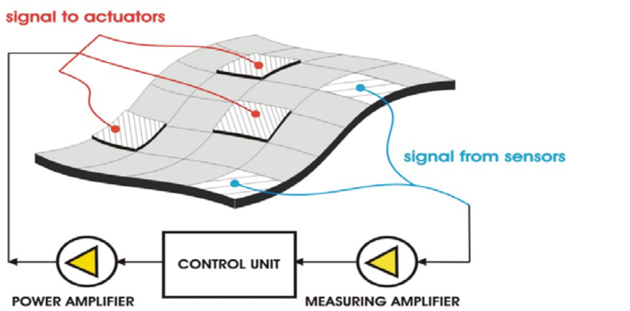

Figure 2: Example of a smart structure with distributed actuators and sensors.

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to the concept of multi-field problems, where several different physical fields (mechanical, thermal, hygroscopic, electric and magnetic field) interact with different levels of influence and importance [5]. In order to make a model of structures, without reference to subatomic dimensions, these five physical fields must be correctly defined. These features are based on measurable material properties (e.g., the Young modulus for the mechanical field). Such properties describe the behavior of a material in a suitable scale for engineering purposes.

In particular applications, when the aforementioned structures appear two-dimensional they are known as plates and shells; when they appear one-dimensional they are known as beams. The advent of new materials in aerospace structures and the use of multilayered configurations have led to a significant increase in the development of three-dimensional or refined two-dimensional theories for the modeling of plates and shells, and refined one-dimensional theories for modeling of beams. Classical two-dimensional models, frequently used in the past for conventional structures, are inappropriate for the analysis of these new elements: unconventional structure modeling involves complicated effects that are not considered in the hypotheses used in classical models. To overcome these limitations, a new set of three-dimensional or refined two-dimensional models have been presented in the literature. These models can have higher orders of expansion in the thickness direction for each considered multi-field variable component, and allow two different multilayered descriptions to be considered: -equivalent single layer models, where the layers are seen as one equivalent plate/shell; -layer-wise models, where each layer is separately considered. The use of layer-wise approaches may be mandatory for an easy and correct imposition of multi-field loads and multi field boundary conditions in multilayered structures (e.g., the imposition of top and bottom values for the electric potential or magnetic potential in smart structures or the imposition and calculation of the temperature profile through the thickness of the structures in order to obtain the correct thermal load) [1,2].

In the case of multilayered structures new complicating effects arise with respect to the isotropic one-layered plates and shells. These effects have a fundamental role in the developments of refined plate/shell theories. For these reasons, classical 2D theories are often inadequate for the analysis of innovative structures, in particular for multi-field problems where the applied loads are defined as field loads, which need an accurate description through the thickness. The main complicating effects introduced by the multilayered structures are the in-plane anisotropy and the transverse anisotropy [1,2]. In the case of laminates made of anisotropic layers, high in-plane anisotropy is exhibited. This feature means that the structure has different mechanical-physical properties in different in-plane directions. If compared to traditional isotropic one-layered structures, multilayered composite plates/shells can show higher transverse shear/normal flexibility with respect to in-plane deformability. A consequence of this in-plane anisotropy is the coupling between shear and axial strains. This coupling leads to many complications in the solution procedure of an anisotropic structure. The 2D models must consider these effects -an example is given by the Higher order Shear Deformation Theory (HSDT)-but depending the magnitude of the in-plane anisotropy, these theories may be not sufficient. A further complicating effect of multilayered structures is the transverse anisotropy: they exhibit different mechanical-physical properties in the thickness direction. Transverse discontinuous mechanical properties cause a displacement field in the thickness direction which can exhibit a rapid change of the slope in correspondence to each layer interface, this effect is known as the zigzag form of the displacement field in the thickness direction [1,2]. It is typical of sandwich structures which have two external stiffer faces and an internal soft core. In order to consider the zigzag form of displacements in deformed multilayered structures, a layer-wise approach can be taken as discussed in [1] or an opportune zigzag function can be added to the displacement field as in [1,2]. In-plane stresses can in general be discontinuous at each layer interface; on the contrary transverse stresses must be continuous at each layer interface for equilibrium reasons. Displacements must be continuous in the thickness direction for compatibility reasons. Therefore, displacements and transverse shear/normal stresses are continuous functions in the thickness direction. Moreover, displacements and transverse stresses have discontinuous first derivatives in the thickness direction with correspondence to each interface because the mechanical properties change in each layer (zigzag effect). The fulfillment of all these requirements is a crucial point in the development of appropriate 2D models for the analysis of multilayered structures. In the case of multilayered anisotropic structures, classical theories, such those based on Cauchy-Poisson-Kirchhoff-Love [1] hypotheses or Reissner-Mindlin [1] hypotheses, fulfill the continuity conditions for displacements, but they do not provide the necessary zigzag form. For these reasons they can often prove inappropriate for the study of multilayered composite plates and shells.

In conclusion, the introduction of innovative multilayered structures has proposed a great challenge for those scientists involved in the development of structural models for the multi-field analysis of modern structures used in the aerospace, aircraft, marine and automotive areas. Refined 1D and 2D models or 3D models must be able to describe complicating effects such as in-plane and transverse anisotropy (zigzag effects and interlaminar continuity) and they must allow a correct description of field loads, such as thermal, hygroscopic, electrical and magnetic loads, which are deeply influenced by behavior through the thickness direction of the structures. These models must be included in advanced tools which will be able to give fundamental information about the stress level, failure indexes, progressive failure analysis, modal analysis and instability phenomena of multilayered structures. An innovative structural tool for the analysis of such problems will permit the design and manufacturing of future structures that will be safer, lighter and more efficient with a great benefit for the community and the environment.

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